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# Using Irrigation to Manage Weeds: A Focus on Drip Irrigation

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Additional information is available at the end of the chapter

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## 1. Introduction

Irrigation has transformed agriculture and shaped civilization since its use in the Fertile Crescent more than 6000 years ago. Access to fresh water for irrigation transformed barren landscapes, allowing populations to move to previously uninhabitable regions. Advances in water management increased the productivity of agricultural systems around the world; supporting substantial population growth. Water consumption for agricultural use accounted for nearly 90% of global water use during the previous century [1] and is responsible for approximately 70% of fresh water withdrawals worldwide [2]. Currently, US water withdrawals for irrigation represent nearly 34% (137 billion gallons/day) of domestic water use [3]. Treating and pumping irrigation water has a significant carbon footprint as well. Pumping groundwater for irrigation requires about 150 kg Carbon/ha [4]. In the US more than 65% of total vegetable acreage and 76% of fruit acreage is irrigated [5]. Irrigating fruit and vegetable crops can increase marketable yields by 200% or more and is necessary to produce the high quality and yields required to be profitable [6]. It was estimated by Howell [5], that irrigated lands account for 18% of total cropped area, but produce approximately 50% of crop value. Due to the large observable increases in yield and quality associated with irrigation, many farmers tend to over-irrigate, viewing it as an insurance policy for growing fruits and vegetables. Irrigation can routinely exceed 10% of input costs in the US [7] and over-irrigating may reduce yields in some instances [8]. Excessive irrigation not only depletes freshwater reserves, but may leach fertilizers and other chemicals from agricultural lands [9-11]. Unnecessary applications of water and fertilizer can also allow weeds to flourish in modern agriculture. While irrigation systems are usually designed and managed with a crop of interest in mind; the impact of irrigation on weed growth is an important component of any mod-

ern production system. The following chapter will address the impact of different irrigation systems on weed management with an emphasis on drip irrigation technologies.

## 2. The influence of irrigation method on weeds

Surface, sprinkler, and drip irrigation are the three primary types of irrigation methods used to grow crops (Figure 1). Within each method, there are several subcategories, each of which varies in water use efficiency, cost, yield, and weed management potential.



**Figure 1.** An irrigation canal for furrow irrigation of cabbage (*Brassica oleracea*) (left), solid set sprinkler irrigation of onion (*Allium cepa*) (center) and surface drip irrigation of recently seeded cabbage (right)

### 2.1. Surface irrigation and the impact on weeds

Surface irrigation, which floods entire fields or supplies water in furrows between planted rows, is the most common type of irrigation used worldwide. Some surface irrigation systems have been operating continuously for thousands of years and have the ability to supply enormous quantities of water over widespread areas. Flood and furrow irrigation can have water use efficiencies per unit of yield ranging from 25-50% of well managed drip irrigation systems [12]. One of the most common crops grown worldwide with flood irrigation is lowland rice (*Oryza sativa*). Flood irrigation can be an integral part of weed management for this crop.

As a semi-aquatic crop, lowland rice production utilizes substantial quantities of water. It was estimated that more than 2m of water are used per crop of rice grown [13]. This underscores the substantial water requirements for lowland rice production; particularly in the initial flooding stages when large quantities of water may be lost prior to saturation [14]. Although it has been reported that rice grown under saturated field conditions did not experience additional water stress and yielded no differently than rice grown under standing water [15,16]; rice which is grown under standing water competes better with weeds than when grown in saturated soils [17, 18]. Although some weeds propagate vegetatively, most develop from seeds; thus flooding can restrict the germination and reduce the abundance of many weeds found in rice paddies [19].

Despite reducing the presence of some weed species, flooded lowland rice fields have over time selected for the presence of semi-or aquatic weed species. To reduce the presence of some of these weeds flooded soils are often tilled. While the primary goal of tillage is to uproot recently germinated weed seedlings; tilling flooded soils can destroy structure and porosity. This results in soils with low infiltration rates, which increases water retention, allowing fields to remain flooded [20].

Weed control in modern rice production is a system where irrigation management is integrated with tillage and planting practices as well as herbicides. Williams et al. [21] reported that weed control was better in fields submerged under 20 cm of water compared to those submerged under 5 cm of water when no herbicides were used. However, when herbicides were included weed control improved significantly at all depths [17]. Flowable-granular herbicide formulations, which are often used in lowland rice production, also rely on standing water for dispersal. Flooded paddy fields allow uniform dispersal of low quantities of herbicides resulting in superior control of weeds [22, 23]. The integration of herbicides into the lowland rice production systems has reduced labor requirements for weed control by more than 80% since the introduction of 2,4-D in 1950, while simultaneously improving overall weed management [23]. Flooding has been an effective weed management technique in lowland rice for thousands of years. Coupled with modern herbicides, farmers can efficiently manage weeds on a large scale. Nonetheless, the high costs of water and demands on finite fresh water resources may result in substantial changes to the current lowland rice production system. The development of “aerobic-rice,” drought tolerant lowland varieties that can yield well on non-saturated soils, may change how irrigation is used to manage weeds in lowland rice. Aerobic-rice is grown in a manner similar to many other grains, with land allowed to dry between irrigation cycles. This has the potential to reduce the reliance on flooding and irrigation water for weed control, likely shifting to chemical or mechanical methods [24].

Furrow irrigation is a common irrigation method where water is sent through ditches dug between raised beds to provide water to plants. Instead of flooding entire fields, only furrows between beds are wetted, allowing water to seep into growing beds through capillary action. Furrow irrigation is commonly used on millions of hectares of crops worldwide; where complex canal networks can move irrigation water hundreds of miles from upland sources to lower elevation growing areas. As would be expected, weed pressure in the irrigated furrows between rows is generally higher than with the rows themselves [25]. To control these weeds, mechanical cultivation may be used, but in many instances, herbicides, either applied to the soil as sprays or through irrigation water, are relied upon. However, the administration of herbicides through furrow irrigation can be challenging. Poor application uniformity, downstream pollution, and inaccuracies due to difficulties in measuring large quantities of water are challenges associated with applying herbicides through surface irrigation water [26, 27]. Chemical choice also is important when applying herbicides in surface irrigation systems. For example, Cliath et al. [27] noted that large quantities of the herbicide EPTC volatilized shortly after application via flood irrigation in alfalfa (*Medicago sativa*);

Amador-Ramirez et al. [28] reported variability in the effectiveness of some herbicides when applied through furrow irrigation compared to conventional methods.

A variant on the typical furrow irrigation system has been developed that combines furrow irrigation with polyethylene mulches and rainwater collection to irrigate crops, while controlling weeds. The production method, called the “ridge-furrow-ridge rainwater harvesting system,” uses woven, water-permeable, polyethylene mulches that cover two ridges as well as a shallow furrow between the ridges [29, 30]. The system is similar to a raised-bed plastic mulch system, with inter-row areas being left in bare soil. However, unlike a traditional plastic mulch system, a furrow is made in the center of the raised bed to collect any rainwater that ordinarily would be lost as runoff from the bed. This system significantly reduces weed pressure in the furrow area and increases yield with the use of a polyethylene mulch, while reducing the need for supplemental irrigation by collecting rainwater [29]. Interestingly, a similar method of irrigation was employed during early experiments with plastic mulch, prior to the introduction of drip irrigation tubing. In these trials irrigation was achieved by cutting furrows in the soil next to the crop, covering them with plastic, and cutting holes in the plastic for the water to penetrate the plant bed [31, 32]

## **2.2. Sprinkler irrigation and the impact on weeds**

Introduced on a large scale in the 1940s, sprinkler irrigation systems are used on millions of ha of crop land. The three primary types of sprinkler irrigation are center pivot, solid set, and reel or travelling gun systems. Sprinkler systems require a pump to deliver water at high pressures and are costlier than surface irrigation systems, but provide superior application uniformity and require less water to operate [33,34]. While center pivot systems require relatively level ground; solid set and reel-type systems can be used on with varied topographies. Because of improved application uniformity, sprinkler irrigation is the method of choice when applying herbicides or other agrichemicals through the irrigation system [26]. Sayed and Bedaiwy [35] noted a nearly 8-fold reduction in weed pressure when applying herbicides through sprinkler irrigation compared to traditional methods. Sprinkler irrigation permits growers to uniformly apply water over large areas, which can allow for proper incorporation of some preemergent herbicides [36]. In addition to applying herbicides, preplant sprinkler irrigation of fields, when combined with shallow tillage events after drying, has been shown to significantly reduce weed pressure during the growing season. This process of supplying water to weed seeds prior to planting, which causes them to germinate, where they can then be managed through shallow cultivation or through herbicide application is termed “stale seed-bedding” and is routinely used by farmers in many parts of the US.

## **2.3. Drip irrigation and the impact on weeds**

Introduced on a large scale in the late 1960s and early 1970s, drip irrigation has steadily grown in popularity [37]. Although drip irrigation is only utilized on approximately 7% of the total irrigated acreage in the US, it is widely used on high value crops such as berries and vegetables [3]. Drip irrigation, if properly managed, is highly efficient with up to 95%



application efficiencies [38]. The productivity of drip irrigation has prompted significant increases (> 500%) in its use over the previous 20-30 years [5]. While drip irrigation is typically expensive and require significant labor to install and manage; the water savings compared to other methods of irrigation have prompted grower adoption. Drip irrigation has several benefits in addition to improved water use efficiencies. By only wetting the soil around plants leaves are kept dry reducing foliar disease and potential for leaf burn when using saline water [37, 39]. Fertilizers, which are easily supplied through drip irrigation, are restricted to an area near active rooting. This leads to more efficient use by the target crop. Because drip irrigation only wets the soil in the vicinity of the drip line or emitter, growers are able to supply irrigation water only in the areas required to grow the crop of interest. Soils between rows are not supplied with water or fertilizer, reducing weed growth. When drip irrigation is coupled with plastic mulch and preplant soil fumigation, weeds can be effectively controlled within rows, leaving only between-row areas to be managed. By restricting weed management to areas between rows growers increase their chemical and mechanical control options. While many farmers may apply preemergent herbicides to between-row areas, weeds that do germinate can be controlled easily with directed sprays of postemergent herbicides with low risk to the crops growing in the plastic mulch. In arid growing regions the combination of plastic mulch and drip irrigation may lead to acceptable weed control without the use of herbicides.

Because drip irrigation can supply limited quantities of water to an area immediately surrounding the crop root zone, it can be ideally suited for insecticide or fungicide injection. The small quantities of water delivered with drip irrigation requires significantly less chemical to maintain a given concentration applied to plants compared to surface or sprinkler irrigation [40]. However, while drip irrigation is one of the most efficient means to deliver chemicals such as systemic insecticides to plants, it is much less effective than comparable sprinkler systems for herbicide applications. The limited wetting pattern and low volume of water used for drip irrigation means that herbicides do not reach much of the cropped area. Within wetted areas herbicides may be degraded prior to the end of the season [26]. Because drip systems are often designed for frequent, low-volume irrigations, soils around plants may remain moist, reducing the efficacy of preemergent herbicides. Fischer et al. [41] reported significantly better weed control when using micro sprinklers compared to drip irrigation in vineyards and orchards. This was due to a reduction in the effectiveness of preemergent herbicides in drip irrigated treatments late in the growing season. The authors speculated that the drip irrigated plants had persistent soil moisture near the emitters resulting in enhanced degradation of the applied herbicides. Drip irrigation is often used in tandem with herbicides; however, they are often applied using conventional sprayers. Therefore, the weed control benefits of drip irrigation are due to the ability to precisely manage and locate water where it will most benefit crops while reducing availability for weed growth. One method that allows growers to precisely locate water in the root zone, below the soil surface, away from weed seeds is subsurface drip irrigation.

### 3. Subsurface drip irrigation

Subsurface drip irrigation (SDI) has been utilized in various forms for more than a century [37, 42]. Presently SDI uses standard drip irrigation tubing that is slightly modified for below-ground use. While typical surface drip irrigation tubing have walls that are usually 8 or 10-mil thick; tubing made specifically for multi-season SDI applications, have walls with a 15-mil thickness. In addition, tubing made specifically for SDI applications may have emitters which are impregnated with herbicides to prevent root intrusion [43]. Because growers are unable to inspect buried tubing, any problems with emitter clogging or cuts in the line may go unnoticed for long periods of time. Subsurface drip irrigation used for the production of high-value crops such as vegetables, which tend to have shallow root systems, may be buried at depths of 15-25 cm [44]. Subsurface drip tubing that is used for agronomic crops such as cotton (*Gossypium spp.*) or corn (*Zea maize*) is generally buried 40-50 cm below the soil surface [45]. Drip irrigation tubing used for agronomic crops is typically left in place for several years in order to be profitable and must reside below the tillage zone to avoid being damaged [45]. Agronomic crops in general tend to be deeper rooted than many vegetable crops allowing them to access water supplied at greater depths. In addition, the deeper placement of the irrigation tubing reduces the potential rodent damage, which can be significant [45, 46].

Drip tubing may be placed during or after bed formation in tilled fields or into conservation tillage fields with drip tape injection sleds (Figure 2). While SDI that is used for a single season may be connected to flexible “lay-flat” tubing at the ends of fields; more permanent installations are generally coupled to rigid PVC header lines.



**Figure 2.** Injection sled for SDI.

Although concern over buried drip tubing collapsing under the pressure of the soil above is justified; properly maintained SDI systems have lasted 10-20 years in the Great Plains without significant problems [45]. For permanent systems, lines must be cleaned and flushed af-

ter every crop if not more frequently. In single-season trials conducted by the author, end of season flow rates were found to be no different between surface and SDI systems placed at a depth of 15 cm (*T. Coolong, unpublished data*). However, when comparing SDI that had been in use for three years for onion production to new SDI tubing, there were slight reductions in discharge uniformity in the used tapes [47].

### 3.1. Subsurface drip irrigation in organic farming

Some of the earliest uses of SDI were not based on enhanced water use efficiency but because drip irrigation tubing on the soil surface could interfere with agricultural equipment, particularly cultivation tools [48]. While many conventional farmers now rely more on chemical weed control than on cultivation, most organic growers must rely exclusively on cultivation to manage weeds. For this reason, SDI is particularly appropriate for organic farming systems. Traditional placement of drip irrigation tubing requires growers to remove the tubing prior to cultivation, increasing labor costs. By burying drip tubing below the depth of cultivation, growers can control weeds mechanically. SDI is routinely used for bare-ground, organic vegetable production at The University of Kentucky Center for Horticulture Research (Lexington, KY, US). This system uses a SDI injection sled (Figure 2) coupled with in-row cultivators to effectively control weeds in a humid environment (Figure 3).



**Figure 3.** Buried drip irrigation tubing entering the soil at the end of a field (top left), a two-row cultivator using side-knives and spring hoes (top right), a rolling basket weeder controlling weeds within and between rows (bottom left), and organically-managed kale and collard (*Brassica oleracea* Acephala group) crops (bottom right) that are grown with SDI and mechanical cultivation for near complete weed control in a humid environment.

In this system, SDI tubing is placed approximately 15 cm below the surface on a shallow raised bed. Using SDI in combination with precision cultivation has allowed for nearly com-



plete control of weeds on an organic farm in an environment which may regularly experience 25 cm or more rain during the growing season.

### 3.2. Subsurface drip irrigation and water use

More than 40 types of crops have been tested under SDI regimes [42]. In most cases yields with SDI were no different than or exceeded yields for surface drip irrigation. In many cases water savings were substantial. However, SDI relies on capillary movement of water upward to plant roots. Soil hydraulic properties can significantly affect the distribution patterns of water around emitters, making interpretation of data difficult when comparing the effectiveness of SDI in different soil types [49]. Trials often report water savings or increased yield in SDI systems compared to surface drip systems for vegetable crop production [44, 50, 51], although some do not [46].

In 2012, studies were conducted at The University of Kentucky Center for Horticulture Research (Lexington, KY, US) comparing SDI at a depth of 15 cm to surface placement of drip irrigation tubing for the production of acorn squash (*Cucurbita pepo*) 'Table Queen'. The soil was a Maury silt loam series, mesic Typic Paleudalfs. Irrigation was controlled automatically with switching-tensiometers placed at a depth of 15 cm from soil surface [52, 53]. Tensiometers were placed approximately 20 cm from plants and 15 cm from the drip tubing which was centered on raised beds. Tensiometer set points were as follows: on/off -40/-10 kPa and -60/-10 kPa for both SDI and surface drip systems. In both moisture regimes the surface applied drip irrigation utilized less water during the growing season than SDI (Table 1). Interestingly, the number of irrigation events and the average duration of each event varied significantly among the surface and SDI treatments when irrigation was initiated at -40 kPa, but were similar when irrigation was scheduled at -60 kPa. Irrigations were frequent, but relatively short for the -40/-10 kPa surface irrigation treatment. Comparable results have been reported in studies conducted in tomato (*Lycopersicon esculentum* syn. *Solanum lycopersicum*) and pepper (*Capsicum annuum*) using a similar management system and set points. However the SDI -40/-10 kPa treatment irrigated relatively infrequently and for longer periods of times. When irrigation was initiated at -60 kPa and terminated at -10 kPa there were differences in water use between the two drip systems, with the surface system being more efficient. However, unlike the -40/-10 kPa treatments, the numbers of irrigation events were not different between the two drip irrigation systems. The difference in the response of the SDI and surface systems when compared under different soil moisture regimes was not expected and suggests that irrigation scheduling as well as soil type may have a significant impact on the relative performance of SDI compared to surface drip irrigation. This should be noted when comparing the performance of SDI and surface drip irrigation systems.

### 3.3. Subsurface drip irrigation for improved weed management

As previously discussed, a key benefit of SDI is a reduction in soil surface wetting for weed germination and growth. Although the lack of surface wetting can negatively impact direct-seeded crops, transplanted crops often have significant root systems that may be wetted without bringing water to the soil surface. Direct-seeded crops grown with

SDI are often germinated using overhead microsprinkler irrigation [51]. The placement of SDI tubing as well as irrigation regime [54] can impact the potential for surface wetting and weed growth. As mentioned previously, SDI is often located 40-50 cm below the soil surface in most agronomic crops, but is typically shallower (15-25 cm) for vegetable crops [51]. Patel and Rajput [55] evaluated five depths (0, 5, 10, 15, and 20 cm) of drip irrigation with three moisture regimes in potato (*Solanum tuberosum*). Soil water content at the surface of the soil was relatively moist for drip tubing placed 5 cm below the surface, while the soil surface remained relatively dry for the 10, 15, and 20 cm depths of drip tubing placement [55]. Because that study was carried out on sandy (69% sand) soils, greater depths may be required to prevent surface wetting on soils with a higher clay content and greater capillary movement of water [56].

Irrigation treatment on/off	Irrigation type	Events	Mean irrigation time	Mean irrigation vol.
kPa		no.	min/event	l•ha <sup>-1</sup>
-40/-10	Surface	48	92	1.25 x 10 <sup>6</sup>
-40/-10	SDI	18	276	1.50 x 10 <sup>6</sup>
-60/-10	Surface	14	201	0.84 x 10 <sup>6</sup>
-60/-10	SDI	14	251	1.06 x 10 <sup>6</sup>

Mean number of irrigation events, irrigation time per event, and irrigation volume for the season 'Table Queen' squash grown with automated irrigation in 2012 in Lexington, KY.

**Table 1.** A comparison of SDI and surface drip irrigation under two automated irrigation schedules.

SDI not only keeps the soil surface drier, but also encourages deeper root growth than surface drip systems. Phene et al. [57] reported greater root densities below 30 cm in sweet corn grown under SDI compared to traditional surface drip. In that study the SDI tubing was placed at a depth of 45 cm. In bell pepper, a shallow rooted crop, SDI encouraged a greater proportion of roots at depths below 10 cm when laterals were buried at 20 cm [58]. Encouraging deeper root growth may afford greater drought tolerance in the event of irrigation restrictions during the production season.

In arid climates SDI has been shown to consistently reduce weed pressure in several crops, including cotton, corn, tomato, and pistachio (*Pistacia vera*) [25, 59, 60]. For example, weed growth in pistachio orchards in Iran was approximately four-fold higher in surface irrigated plots compared to those with SDI [59]. In humid regions, benefits may depend on the level of rainfall received during the growing season; however, a reduction in the consistent wetting of the soil surface should allow for a reduction in weed pressure, particularly when coupled with preemergent herbicides (Figure 4).

Processing tomatoes represent one of the most common applications of SDI in vegetable crops. The impact of SDI (25 cm below the soil surface) and furrow irrigation on weed

growth were compared in tomato [25]. In that trial the authors reported a significant decrease in weed growth in plant beds and furrows with SDI compared to furrow irrigation. When no herbicides were applied, annual weed biomass was approximately 1.75 and 0.05 tons per acre dry weight in the furrow and SDI treatments, respectively [25]. With herbicides, both irrigation treatments had similar levels of weed biomass. However, in that study, weed biomass in the SDI non-herbicide treatment was similar to the furrow irrigation with herbicide treatment, suggesting that when using SDI, herbicides may not be necessary in arid environments.



**Figure 4.** The difference in weed growth approximately 10 days after transplanting between acorn squash (*Cucurbita pepo*) which were subjected to SDI at a depth of 15 cm below the soil surface (*left*) and surface drip irrigation (*right*). A preemergent herbicide (halosulfuron methyl, Sandea™) was applied to all plots

A similar trial compared SDI and furrow irrigation across different tillage regimes with and without the presence of herbicides in processing tomato [60]. In that study, both conservation tillage and SDI reduced the weed pressure compared to conventional alternatives. However, when main effects were tested, SDI had the largest impact on weed growth of any treatment. Main effects mean comparisons showed that SDI treatments had weed densities of 0.5 and 0.6 weeds per m<sup>2</sup> in the planting bed in years one and two of the trial, respectively, compared to 17.9 and 98.6 weeds per m<sup>2</sup> in the plant bed for furrow irrigated treatments. As would be expected, SDI substantially reduced weed populations in the furrows between beds as they remained dry during the trial. In this trial SDI had a greater impact on weed



populations than herbicide applications. The authors concluded that SDI could reduce weed populations sufficiently in conservation tillage tomato plantings in arid environments such that herbicides may not be necessary [60]. In another related trial, weed populations were evaluated for processing tomatoes grown with SDI and furrow irrigation under various weed-management and cultivation systems [46]. In this trial, the authors noted an increase in weed densities in the furrow system compared to SDI within the planting bed and furrows. However, there was no significant difference in the total weed biomass in the plant bed comparing the two irrigation systems [46]. The authors did note that the majority of the weeds in the SDI treatment were in the plant row and not evenly distributed across the bed, indicating that the outer regions of the plant bed were too dry to support weed germination or growth. Interestingly, when the relative percentages of weeds are extrapolated from the results provided, *Solanum nigrum* constituted 76% of the weed population in the plant beds of SDI treatments, but 52% of the weed population in the furrow irrigated beds. Although the sample size from that study is too small to make statements regarding selection pressures for weed species in the irrigation systems evaluated, it may give insight into why the authors reported a significant difference in numbers of weeds, but not biomass. *Solanum nigrum* can grow quite large and may have contributed a substantial amount of biomass in the SDI plots, despite having fewer numbers of weeds present. In this trial the furrow irrigation treatments had significantly greater yields than the SDI treatments [46]. The authors suggested that this was not due to a flaw in the SDI system, but poor management late in the season. The relatively small amounts of water used in drip irrigation underscore the need for proper scheduling; otherwise water deficits can occur, resulting in poor yields.

#### 4. Efficient management of drip irrigation

Appropriate management of irrigation requires growers to determine when and how long to irrigate. A properly designed and maintained drip irrigation system has much higher application efficiencies than comparable sprinkler or surface irrigation systems [37]. However, even with drip irrigation, vegetable crops can require large volumes of water - more than 200,000 gallons per acre for mixed vegetable operations in Central Kentucky, US [61]. Poorly managed drip irrigation systems have been shown to reduce yields (Locascio et al., 1989) and waste significant quantities of water. Just 5 h after the initiation of drip irrigation, the wetting front under an emitter may reach 45 cm from the soil surface, effectively below the root zone of many vegetables [62]. When drip irrigation is mismanaged, a key benefit – limiting water available for weeds, is lost. The ability to precisely apply water with drip irrigation means that a very high level of management can be achieved with proper scheduling [63].

Irrigation scheduling has traditionally been weather or soil-based; although several plant-based scheduling methods have been proposed [64, 65]. In weather-based scheduling, the decision to irrigate relies on the soil-water balance. The water balance technique involves determining changes in soil moisture over time based on estimating evapotranspiration (Et) adjusted with a crop coefficient [66]. These methods take environmental variables



such as air temperature, solar radiation, relative humidity and wind into account along with crop coefficients that are adjusted for growth stage and canopy coverage [64]. Irrigating based on Et can be very effective in large acreage, uniformly planted crops such as alfalfa, particularly when local weather data is available. However, irrigating based on crop Et values for the production of vegetable crops is prone to inaccuracies due to variations in microclimates and growing practices. Plastic mulches and variable plant spacing can significantly alter the accuracy of Et estimates [67, 68]. Furthermore the wide variability observed in the growth patterns in different cultivars of the same vegetable crop can substantially alter the value of crop coefficients at a particular growth stage. In many regions of the US, producers do not have access to sufficiently local weather data and the programs necessary to schedule irrigation.

An alternative to using the check-book or Et-based models for irrigation is to use soil moisture-based methods. Perhaps the simplest and most common method is the “feel method,” where irrigation is initiated when the soil “feels” dry [69]. Experienced growers may become quite efficient when using this method. More sophisticated methods of scheduling irrigation may use a tensiometer or granular matrix type sensor [6, 70-72].

These methods require routine monitoring of sensor(s), with irrigation decisions made when soil moisture thresholds have been reached. This requires the development of threshold values for various crops and soil types. Soil water potential thresholds for vegetable crops such as tomato and pepper have been developed [6, 72, 73]. Drip irrigation is well suited to this type of management as it is able to frequently irrigate low volumes of water allowing growers to maintain soil moisture at a near constant level [6, 52, 53, 72]. In some soils, high-frequency, short-duration irrigation events can reduce water use while maintaining yields of tomato when compared to a traditionally scheduled high-volume, infrequent irrigation (Table 2) [52, 71].

2009				2010			
Irrigation on/off	Events	Mean irrigation time	Mean irrigation vol.	Events	Mean irrigation time	Mean irrigation vol.	
kPa	no.	min/event	l•ha <sup>-1</sup>	no.	min/event	l•ha <sup>-1</sup>	
-30/-10	39	110	1.30 x 10 <sup>6</sup>	28	144	1.22 x 10 <sup>6</sup>	
-30/-25	59	91	1.63 x 10 <sup>6</sup>	22	140	0.93 x 10 <sup>6</sup>	
-45/-10	21	221	1.41 x 10 <sup>6</sup>	22	167	1.11 x 10 <sup>6</sup>	
-45/-40	76	40	0.92 x 10 <sup>6</sup>	18	146	0.79 x 10 <sup>6</sup>	
Mean number of irrigation events, irrigation time per event, and irrigation volume for the season 'Mountain Fresh' tomato grown under five automated irrigation regimes in 2009 and 2010 in Lexington, KY.							

**Table 2.** A comparison of high frequency short duration to more traditional infrequent but long duration irrigation scheduling using soil moisture tension to schedule irrigation (Adapted from [52])

Coolong et al. [52] reported that irrigation delivered frequently for short durations so as to maintain soil moisture levels in a relatively narrow range could save water and maintain

yields, but efficiencies varied depending on season and the soil moisture levels that were maintained. In two years of trials, irrigation water was most efficiently applied when soil moisture was maintained between -45 and -40 kPa for tomatoes grown on a Maury Silt Loam soil. However, when soil moisture was maintained slightly wetter at -30 to -25 kPa, the relative application efficiency was affected by growing year (Table 2). Therefore, while an effective method, soil moisture-based irrigation scheduling may produce variable application efficiencies and should be used in concert with other methods.

After more than 40 years of research with drip irrigation, results suggest that a mix of scheduling tactics should be employed to most efficiently manage irrigation. The application efficiencies of several different management methods were determined by DePascale et al. [12]. Those authors estimated that when compared to a simple timed application, the use of soil moisture sensors to schedule irrigation would increase the relative efficiency of drip irrigation by 40-50%. Using a method incorporating climate factors and the water-balance technique, one could increase relative efficiency compared to the baseline by 60-70%. However, when soil moisture sensors were combined with Et-based methods, the relative efficiency of drip irrigation could be increased by more than 115% over a fixed interval method. Therefore multiple strategies should be used to optimize drip irrigation scheduling. This ensures maintaining yields while reducing excessive applications of water, reducing the potential for weed growth.

## 5. Conclusions

Irrigation management is essential to developing a holistic system for weed management in crops. As water resources become costlier, drip irrigation technologies will become more widely utilized by growers worldwide. Although drip irrigation may be adopted due to water savings, the impact of drip irrigation on weed control is noteworthy. The ability to reduce soil wetting will allow for improved weed control over sprinkler and surface irrigation systems. Furthermore, precisely locating water in the root-zone without wetting the soil surface will make SDI more attractive to growers, despite the higher installation costs. In addition, SDI is now being implemented on large acreages for the production of grain crops, particularly corn, in the Midwestern US. With the increase in adoption of SDI, new technologies will be developed to overcome some of the limitations of that system. Future research will likely continue to develop management tactics combining multiple scheduling strategies such as Et and soil moisture-based irrigation [12] and its application for managing SDI on a wider range of crops and soil types.

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